the losses of the movable end of the cavity, which is at room temperature. Because the microwave thermal energy is concentrated in the modes of the cavity, its frequency distribution is sharply peaked at the resonant frequencies of the cavity.

Experimentally, the detection has been observed by tuning the cavity through its range, and, whenever the frequency of the cavity is coincident with one of the detecting frequencies, the fluorescence exhibits a pronounced increase. Fig. 3 illustrates a typical response as a pair resonance is scanned. The frequency detected may be inferred from measurements of the intervals between related resonances. In the experiments, several frequencies representing activity by both the second and fourth neighbor pairs were observed. Of these, the two frequencies that have been measured most accurately are due to the fourth neighbors; these responses occurred at 612 Gc ± 3 Gc (20.4 ± 0.1 cm^{-1}) and 426 Gc± 6 Gc (14.2 ± 0.2 cm^{-1}). These two lines had apparent widths of approximately 500 Mc.

At 4.2°K, tuning a cavity resonance through one of the frequencies above caused an increase of 20 per cent in the total fluorescence picked up by the bolometer; this represents a power change of roughly 5×10^{-8} watts. Because of the nature of the microwave power source, it is very difficult to estimate the power input to the detector. Taking account of the loss of the silver coating, and the multiplicity of modes contributing to the excitation, a probable upper bound to the power input to the ruby is 10^{-10} watts. Within the limitations of this estimate, the net up-conversion gain is 500. The frequency ratio of the output to input signals is in the range of 700:1000.

There has been no measurement of the time constant of this detector, though it is assumed that the detection time constant is about the same as another unmeasured quantity, the spin-lattice relaxation time. The fact that the detector does operate suggests that the spin-lattice relaxation time is rather long, very likely too long for communications applications. One may anticipate, however, the possibility of using such a detector, located in a totally cooled resonator, as a submillimeter radiometer.

Perhaps more important than the direct detection potentialities of the system that has been studied, is the evidence this experiment provides for the existence of an absorption involving the $\Delta S = 1$ transitions by the Cr-ion pairs in ruby; this effect is denied by simple isotropic spin-exchange. Its existence opens the way to other quantum electronics systems in the submillimeter region using this readily avilable material.

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A Measurement of Bolometer Mount Efficiency at Millimeter Wavelengths*

INTRODUCTION

In recent studies of a pulsed source of millimeter and submillimeter waves[1] the average power of the signals generated was below the sensitivity of common power meters that utilize barretters or thermistors. A device was required that measured peak power or energy per pulse.

A method for measurement of peak power employing bolometers had been developed for power levels of a few milliwatts in the centimeter wavelength range (up to K band).[2] In this method the nearly linear resistance rise of a barretter upon application of a RF rectangular pulse is differentiated. The differentiation produces a step function, and a peak reading instrument measures its amplitude.

This method was adapted to measure peak power in the order of tens of microwatts in the millimeter and submillimeter range. A simple RG-99 waveguide mount was built to hold a commercial bolometer element normally used in RG-98 waveguide. The bolometer (nominally 200 Ω) was connected to a 6-v battery through a 1000-Ω resistor. The transient changes of the voltage across the bolometer were observed on an oscilloscope through an ac-coupled amplifier. Since the observed changes were generally less than one per cent of the total bias voltage on the bolometer, the arrangement gave an essentially constant-current supply.

In use, the microwave pulse caused the temperature of the barretter to increase. The thermal time constant was much shorter than the inter-pulse period, so that the temperature would fall off to the initial value before the next pulse arrived. This change in temperature was accompanied by a change in resistance. The circuit described above provided a video pulse with an amplitude proportional to the change in resistance. It is readily shown that the area under the video pulse represents the total microwave energy absorbed and that the peak power of a rectangular pulse is proportional to the amplitude of the video pulse ΔV, and is given by

$$p = \frac{\tau}{\Delta t} \frac{(R + r_0)^2}{R} \frac{\Delta V}{E \dfrac{dr}{dp}},$$

where τ is the thermal time constant of the bolometer, Δt is the length of the rectangular pulse, E is the bias voltage, R and r_0 are the bias and barretter resistances, respectively, and ΔV is the peak value of the video pulse. The rate of change of barretter resistance with power was calibrated at dc. The calibration sensitivity obtained was one millivolt per milliwatt-microsecond.

MEASUREMENT OF MOUNT EFFICIENCY

The bolometer, although mounted in waveguide, was generally used for measurements in a quasi-plane-wave setup such as shown in Fig. 1. It was essential, therefore, to determine how much of the power incident on the parabola was actually absorbed in the bolometer wire itself. A measurement of "mount efficiency" was therefore made in which the parabola, horn and connecting waveguide were all considered part of the mount itself.

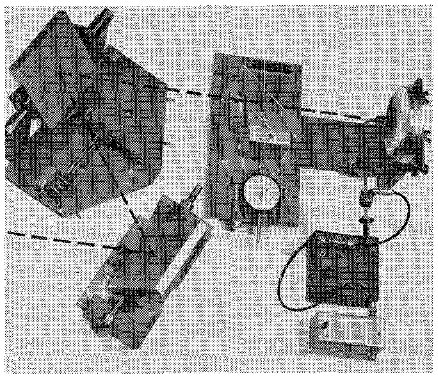

Fig. 1—Experimental arrangement.

The experimental arrangement was similar to that of Fig. 1. The apparatus is shown in the configuration used to calibrate the coupling coefficient of the diagonal, dielectric slab used as a directional coupler. The coupling was determined directly from a measurement of the Q and the coupling coefficient of the parallel-plate resonator shown. The detector was then moved to replace the upper plane mirror, and the laboratory itself was found to be a satisfactory termination for the straight-through arm of the coupler.

The impedance of the detector was measured[3] for various values of bolometer resistance and plotted on a Smith Chart. From the extrapolated values of impedance for zero and infinite bolometer resistance, the mount efficiency was readily obtained. The extrapolation was facilitated by utilizing the tuning stub on the bolometer mount. For each value of bolometer resistance, an impedance circle was plotted as the tuner was adjusted. The circles were tangent at a common point which was taken to be on the zero-resistance circle for the bolometer. The points of maximum sensitivity on each circle defined another circle (the transformed "resistive axis" of the bolometer itself) orthogonal to the family of experimental circles. This provided adequate data to average out experimental errors. The mount efficiency was then computed by a method analogous to that of Kerns.[4]

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[1] P. A. Szente, R. H. Miller, and K. B. Mallory, "Production of Submillimeter Waves by Bunched, Relativistic Electrons," presented at the Millimeter Wave Conference, Orlando, Fla.; January 7–10, 1963.

[2] Sperry Microwave Electronics Company, *Monitor*, vol. 1; January, 1961.

[3] P. A. Szente, R. H. Miller, and K. B. Mallory, "On the Measurement of Detector Impedance," presented at the Millimeter and Submillimeter Wave Conference, Orlando, Fla.; January 7–10, 1963.

[4] D. M. Kerns, "Determination of Efficiency of Microwave Bolometer Mounts from Impedance Data," Nat'l. Bur. Standards Rept. CRTL-9-6; August, 1948.

The over-all mount efficiency was measured at 5.4 millimeters and 2 millimeters using the above arrangement. The measured efficiency at these wavelengths was found to be 50 per cent and 25 per cent, respectively.

This bolometer provided a means of measuring peak powers as low as 20 microwatts. As it is a device that measures the RF energy converted into heat, its response is proportional to the RF power. This bolometer provided a detector of known response law, which is essential to accurately perform impedance measurements.

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Injection Phase Locking of Two-Cavity Klystron Oscillators*

Injection phase locking of reflex klystron oscillators was recently reported by Mackey in these Transactions.[1] Two-cavity klystron oscillators may be phase locked in a similar manner. Injection locking affords a means of two-cavity oscillator stabilization that obviates the necessity for elaborate beam voltage and temperature control. Excellent frequency stability may be obtained by locking the two-cavity oscillator to a signal derived from either a crystal oscillator or a frequency standard. Fig. 1 shows a two-cavity oscillator injection locking system.

An estimate of the locking bandwidth can be made by adapting the low-frequency theory of Adler[2] to the two-cavity oscillator. Since only a fraction of the output power is fed back to the input cavity to sustain oscillation, the input cavity is lightly coupled to the load. The input cavity typically receives 30 per cent of the injected locking power. The total locking bandwidth $2\Delta f$ may be expressed as

$$2\Delta f = \frac{f_o}{Q_L}\left(\frac{0.3P_1}{P_o}\right)^{1/2},$$

where f_o = oscillator frequency, Q_L = total loaded Q of input cavity, P_1 = locking power, P_o = output power.

Locking measurements were made on a Sperry SOU-293, two-cavity oscillator at 17.5 Gc. A calibrated spectrum analyzer was used to observe the locking range. Fig. 2

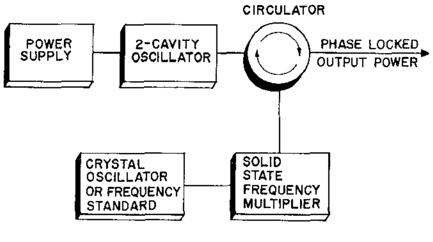

Fig 1—Injection phase-locking system for two-cavity oscillators.

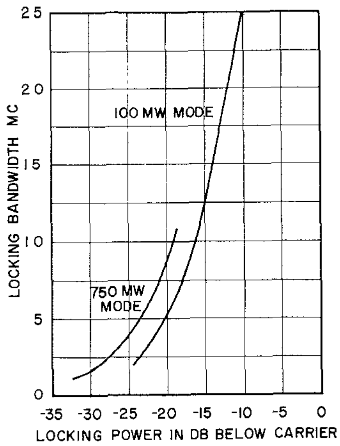

Fig. 2—Phase-locked bandwidth vs injected-locking power for SOU-293, 17.5 Gc.

shows the locking bandwidth vs locking power for the two modes of the SOU-293. The curves differ because the increased electron beam loading at the higher power mode produces a lower value of loaded Q.

Two-cavity oscillators require higher values of locking power than reflex klystrons for a given locking bandwidth since their loaded Q's are higher and only about 30 per cent of the locking power enters the input cavity. One compensating factor is that the higher inherent stability of the two-cavity oscillator requires less locking bandwidth and thus less locking power in many applications.

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[1] R. C. Mackey, "Injection locking of klystron oscillators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-10, pp. 228–235; July, 1962.

[2] R. Adler, "A study of locking phenomena in oscillators," Proc. IRE, vol. 34, pp. 351–357; June, 1946.

TEM Mode in a Parallel-Plate Waveguide Filled with a Gyrotropic Dielectric*

The purpose of this communication is to point out that a parallel-plate waveguide filled with a gyrotropic dielectric, can support a TEM mode which has special characteristics.

Consider a waveguide formed by two perfectly conducting plane parallel plates. The lower and the upper plates occupy, respectively, the regions $-\infty<x<\infty$, $-\infty<y<\infty$, $z=0$ and $-\infty<x<\infty$, $-\infty<y<\infty$, $z=a$, where x, y and z form a right-hand rectangular coordinate system (Fig. 1). The space between the parallel plates is filled uniformly with a homogeneous plasma, which for the sake of simplicity is assumed to be an incompressible, loss-free electron fluid, with stationary ions that neutralize the electrons, on the average. A line source given by

$$E_x(x, 0) = E_0\delta(x) \qquad (1)$$

is assumed to be present inside the waveguide, along the y axis. Only the linear, time-harmonic problem is considered. The harmonic time dependence $e^{-i\omega t}$ is implied for all the field components. An external magnetic field is assumed to be impressed throughout the plasma in the y direction.

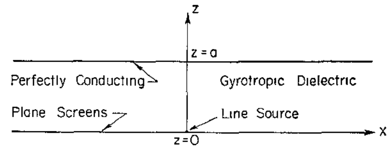

Fig. 1—Geometry of the problem.

Under these assumptions, the plasma becomes equivalent to an anisotropic dielectric. The line source excites only the E mode, for which the magnetic field has only a single component, namely, $H_y(x, z)$. It can be shown [1] that $H_y(x, z)$ satisfies the wave equation

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}+k^2\right]H_y(x, z) = 0, \qquad (2)$$

where

$$k^2 = \omega^2\mu_0\epsilon_0\frac{\epsilon}{\epsilon_1} = k_0^2\frac{\epsilon}{\epsilon_1} = \frac{k_0^2(\epsilon_1^2-\epsilon_2^2)}{\epsilon_1} \qquad (3)$$

$$\epsilon_1 = \frac{\Omega^2-R^2-1}{\Omega^2-R^2}; \quad \epsilon_2 = \frac{R}{\Omega(\Omega^2-R^2)}$$

$$\epsilon = \epsilon_1^2-\epsilon_2^2 = \frac{(\Omega^2-\Omega_1^2)(\Omega^2-\Omega_3^2)}{\Omega^2(\Omega^2-\Omega_2^2)}; \qquad (4)$$

and

$$\Omega_{1,3} = \frac{\mp R+\sqrt{R^2+4}}{2}; \quad \Omega_2 = \sqrt{1+R^2} \qquad (5)^1$$

$$\Omega = \frac{\omega}{\omega_p}, \qquad R = \frac{\omega_c}{\omega_p}. \qquad (6)^1$$

Also μ_0 and ϵ_0 are the permeability and dielectric constant pertaining to vacuum; ω_p and ω_c are, respectively, the plasma and the gyromagnetic frequency of an electron.

The nonvanishing components $E_x(x, z)$ and $E_z(x, z)$ of the electric field are obtained

* Received March 28, 1963; revised manuscript received May 6, 1963.

[1] The notation used in (5) and (6), though frequently used in the literature, is different from the URSI notation as given in J. A. Ratcliffe, "The Magneto-Ionic Theory," Cambridge University Press, Cambridge, England; 1959.